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# The Dependence of Actual Laser Cutting Speed on CNC Sheet Equipment on Number of NC Program Commands for Metal Grades 1.0114 and AWAIMg3

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**Abstract.** One of the complex optimization problems arising in technical applications is the cutting path problem for CNC sheet metal cutting machines. This problem is to optimize the tool path for the CNC technological equipment when cutting a fixed set of parts allocated on sheet metal. The time of cutting process is one of objective functions for the optimization problem. This objective function depends on six parameters of cutting process: 1) cutting speed; 2) lengths of the cutting tool path; 3) speed of idling motion of tool; 4) length of idling motion; 5) number of piercings; 6) time of one piercing. When programming NC program, speed of cutting is defined by the user of the CAM (Computer-Aided-Manufacturing) system and considered as a constant. However, this is actually not the case. Consequently, the problem of exact calculation of objective function is arisen. In order to solve this problem, the correction coefficients for the cutting speed value defined by the user must be calculated. Obviously, these coefficients will vary for different thicknesses and grades of metal. The paper presents the results of investigates, which made it possible to find the functional dependences of the cutting speed for the CNC laser cutting machine (CO2) on the number of NC program commands for the following metal grades: 1.0114 (thickness  $\Delta = 1-10$  mm) and AWAIMg3 ( $\Delta = 1-5$  mm). The statistical materials of experiments were processed by using software “Mathcad”. The received results show that the actual average value of cutting speed is monotonically decreasing function depended on number of NC program commands. In addition, the calculation of the actual cutting speed provides not only an accurate calculation of the value of the objective function, but also, as a result, the correct finding of the optimal tool path

**Keywords:** CNC laser cutting machines, NC Program, cutting speed, tool path problem, optimization, objective functions, Metal Grades 1.0114 and AWAIMg3

## 1. Introduction

Tool path problem for CNC sheet cutting machines that belongs to the class of NP-hard problems of continuous-discrete optimization is one of the most complex optimization problems in development of NC programs by using Computer Aided Manufacturing (CAM). CAM systems are using for generation NC programs for different CNC equipment. During NC program development the users of



CAM systems have to optimize the cutting tool path for CNC equipment. The considering problem is to optimize the tool path for the CNC equipment when cutting a fixed set of parts allocated on sheet metal. As to optimization tool path problem for CNC thermal cutting equipment the optimization of machining parameters for cutting process provides in particular the minimizing of machining time and of others cost optimization criterions, i.e. time of the cutting process is one of the objective functions of the optimization problem. At present, CNC laser/plasma/gas/water-jet machines are actively used in various industries for cutting of sheet material. During development of NC programs there is a need to take into account some important technological features and constraints arising in the process of part sheet cutting on CNC equipment, namely: piercings of sheet material; points of switching tool off; lead-in/lead-out path of tool moving; cutting airtime motion of tool (see, in particular, [1]). The time of the cutting process as the objective function depends on six parameters of cutting process: 1) speed of cutting; 2) lengths of cutting path; 3) speed of tool idling motion; 4) length of idling motion; 5) number of piercings; 6) time of one piercing. Time of cutting process ( $T_{cut}$ ) can be calculated by next formula:

$$T_{cut} = L_{on}/V_{on} + L_{off}/V_{off} + N_{pt} \cdot t_{pt}. \quad (1)$$

Here  $L_{on}$  and  $L_{off}$  accordingly are length of cutting and idling motions;  $V_{on}$  and  $V_{off}$  accordingly are speeds of cutting and idling motions;  $N_{pt}$  is number of piercings;  $t_{pt}$  is time of one piercing.

In the scientific literature, when describing algorithms for solving the tool path problem for CNC sheet cutting machines, as usually, a narrow class of problem is considered. The first classification of optimization problems was given by Hoeft and Palekar [2]. They allocated 3 main classes of the task: Continuous Cutting Problem (CCP), Endpoint Cutting Problem (ECP) and Intermittent Cutting Problem (ICP). A detailed overview of the existing classification of the cutting path problem is given by Dewil et al. [3]. Based on conception of contours cutting by segment the new class of the optimization tool path problem is presented by Petunin [4] – Segment Continuous Cutting Problem (SCCP). A lot of publications describe the use of the well-known discrete optimization model GTSP (The Generalized Traveling Salesman Problem) and ECP (see, in particular Jing and Zhige [5], Yu and Lu [6], Chentsov A.G. and Salii [7], Chentsov A.G. et. al [8], Helsgaun et. al [9], Dewil et al. [10-12]). The difference between described above classes of the problem is determined by the difference in the rules for selecting the possible pierce points and in used cutting technique.

In all papers the cutting speed  $V_{on}$  (1) is considered as constant value. However as practice shows this is actually not the case. There are several factors affecting the change of tool speed in different metals during thermal cutting. It is main reason that the problem of exact calculation of objective function for optimization of tool path is arisen. In order to solve this problem, the correction coefficients for the cutting speed value must be calculated. Obviously, these coefficients will vary for different thicknesses and grades of metal. It should be noted, in particular, that the question of exact calculation of  $V_{on}$  values is remained open, then there is a need of research in order to calculate the correction parameters of  $V_{on}$  values and consequently the cutting time and also cutting cost. Below we formulate the main hypotheses in order to determine what kind of factors affect on changing of tool speed during thermal cutting on CNC equipment and what do not affect. Based on received results the exact calculation of objective function of tool path problem is performed.

## 2. Problem of exact objective function calculation

As we noted above when programming NC program,  $V_{on}$  is defined by the user of the CAM system and considered as a constant. However, this is actually not the case (see, in particular, [13]). Consequently, the problem of exact calculation of objective function is arisen. In order to solve this problem, the correction coefficients for the cutting speed value must be calculated. Obviously, these coefficients will vary for different thicknesses and grades of metal.

In order to determine what kind of factors affects on changing of tool speed during thermal cutting on CNC equipment the following hypotheses are tested:

- Hypothesis 1: The working speed  $V_{on}$  depends on temperature change of sheet metal during

cutting process;

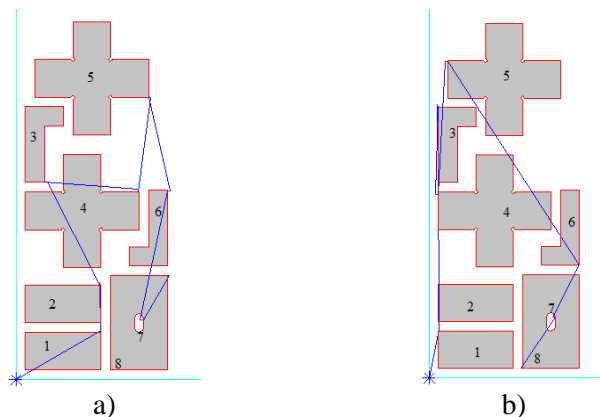
- **Hypothesis 2:** The working speed  $V_{on}$  depends on complexity of parts geometry;
- **Hypothesis 3:** The working speed  $V_{on}$  depends on number of commands in NC program.

### 2.1 Influence of temperature change on cutting speed $V_{on}$

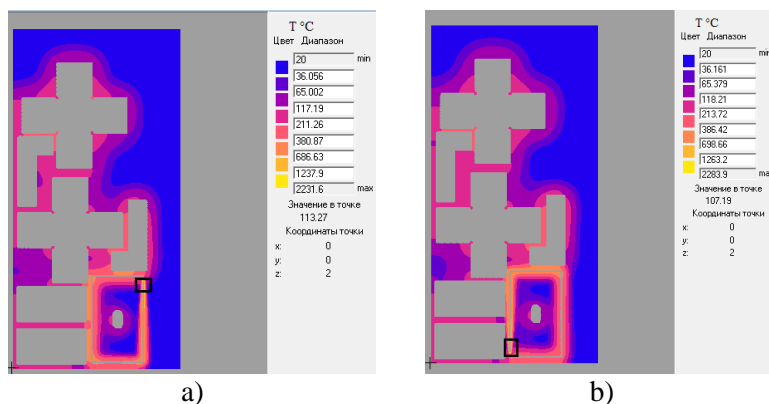
The following research has been performed in order to determine if temperature change of sheet metal during cutting process affects on working speed  $V_{on}$  or not. The experiment was performed using CO<sub>2</sub> laser cutting equipment ByStar3015 for material 1.0114 (thickness  $\Delta=2\text{mm}$ ).

As practice shows the thermal deformations occur during thermal cutting on CNC equipment (in particular during laser cutting). But the value of temperature during cutting process can be reduced by using Part Hardness Rule [1]. Therefore in order to evaluate the influence of temperature change on working speed  $V_{on}$  for each of nesting results we assign the cutting tool path complying with Part Hardness Rule (Fig.1a) and without complying with this rule (Fig.1b).

Fig.1 presents result of nesting and cutting tool path, in so doing, number of parts  $N=7$ , number of contours  $n=8$ . The numbers 1-8 are sequence of contours cutting. The red lines on Fig.1 are cutting tool movements, the blue lines are idling tool movements. The position of parts and distances between them are the same for nesting from Fig.1a) and Fig.1b). The difference is determined by the difference in the rules for selecting the possible pierce points and contour bypass direction. The calculation of temperature fields during cutting process have been performed by special software [14]. The results of thermal field calculation are presented in Fig.2 a),b) for nesting from Fig.1a),b)



**Fig.1.** The tool path construction complying with Part Hardness Rule (a) and without complying with this rule (b)



**Fig.2.** The temperature change during laser cutting process complying with the Part Hardness Rule (a) and without complying with this rule (b)

The calculation was performed for 1.0114  $\Delta=2\text{ mm}$ . For the first case (Fig.1a) the piercing is selected by using Part Hardness rule (Fig.2a), i.e. the end of cutting should happen near “hard” (not

cut yet) sheet zone. The average temperature of selected window (black rectangle) near point of tool switching off is  $492.9^{\circ}\text{C}$  (Fig.2a). Fig.2b) presents the thermal field for case (Fig.1b) without complying with the Part Hardness Rule. The average temperature of selected window (black rectangle) near point of tool switching off is  $556.3^{\circ}\text{C}$ , which is 11,4% higher than the average temperature in the same area for case on Fig.2a). The real values of  $T_{cut}$  were measured during laser cutting on ByStar3015 and they equal respectively 36,8 sec for nesting from Fig.1a and 36,2 sec for nesting from Fig.1b).

Consequently the difference  $V_{on}^a$  in the case using Part Hardness Rule and  $V_{on}^b$  without complying with this rule is 1.5%. The similar researches have been conducted using other contours in the case of cutting material 1.0114 ( $\Delta=2\text{mm}$ ). The average value of the difference and  $V_{on}^b$  is 1-1,8%. Consequently, conducted experiment on a CNC laser cutting machine did not confirm hypothesis 1 (i.e.  $V_{on}^a \approx V_{on}^b$ ).

## 2.2 Influence of complexity of parts geometry on cutting speed $V_{on}$

A series of experiments were performed and some results showed that the working speed depends on geometrical configuration of parts [15], i.e. the more straight section in the nesting the working speed is increased, as well as in the case of rectangle parts with and without rounding on the corner if there are rounding on the corner, the working speed will increase (and besides the more rounding the working speed increases). However, this increase was negligible. In the conducted experiments also the quality of cutting process were investigated and the substantial dependencies cutting speed on complexity of parts geometry were not yet been received. A more significant impact, as will be shown below, is exerted by the number of commands in NC program (Hypothesis 3). However, Hypothesis 2 is still awaiting study

## 2.3 Influence of commands number in NC program on cutting speed $V_{on}$

As for the dependencies working speed on number of commands in NC program the following research was performed in order to determine if number of commands in NC program affects on working speed or not. The experiment was performed using laser  $\text{CO}_2$  cutting equipment ByStar3015 for material 1.0114 and AWA1Mg3 with various thicknesses. The 150 NS programs has been developed for each of material grades and each thickness. In each NC program the working speed was set by nominal speed -  $V_{on}^{nom}$ . The some practical results of determining dependence of cutting speed on number of NC program commands are given below.

The statistical materials were processed by using "Mathcad". Based on received results the following upshots were made:

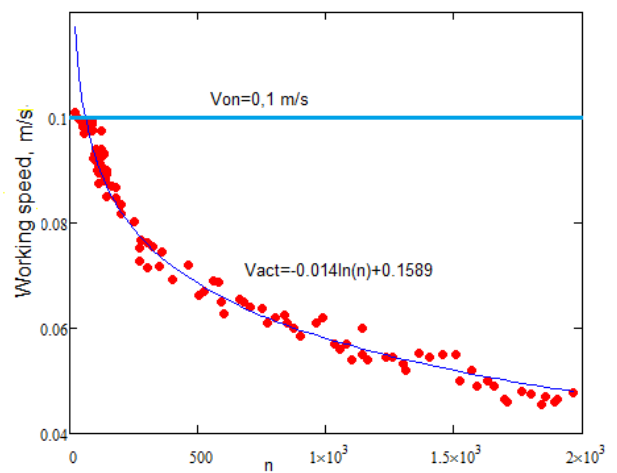
- 1) The actual average value of cutting speed  $V_{act}$  is monotonically decreasing function depending on number of commands in NC program (Fig.3);
- 2) The predetermined cutting speed  $V_{on}^{nom}$  coincides with the actual average speed when the numbers of commands reaches a certain threshold value  $N$ . If the number of commands  $n < N$ , then the actual speed will be greater than predetermined cutting speed, if the number of NC program commands is increased ( $n > N$ ) then the actual speed will be less than  $V_{on}^{nom}$  (in the experiments the reduction of average  $V_{act}$  value compared with  $V_{on}^{nom}$  in NC program reaches to 70%);
- 3) The threshold value  $N$  is varied for different thickness and grade of material.

In order to present the results of computational experiments the following notations are introduced:  $n$  – number of NC program commands;  $V_{act}$  – the actual speed of cutting tool;  $N$  – the number of commands when  $V_{act} = V_{on}^{nom}$ ;  $\sum_n \varepsilon_n^2$  – the deviation squares sum of the original data from the values of the approximation functions at these points.

When approximation the actual speed dependence presented on point chart on the number of commands with approximating curves in “Mathcad”  $\sum_n \varepsilon_n^2 \rightarrow 0$  for all values of studied grade materials and thickness are achieved using logarithmic approximation function. Fig.3 presents following results for material of AWAIMg3 with  $\Delta=1$  mm. Similar results were obtained for AWAIMg3 with  $\Delta=1-5$  mm and 1.0114 with  $\Delta=1-10$  mm that are given in table 1.

The generalized formulas for calculating of cutting tool speed by example CNC laser cutting machine ByStar3015 are presented in table 1. The received results confirm hypothesis 3.

Based on proposed results the calculation of objective function (1) can be performed with correction of working speed values depending on number of commands in NC program for each valid option of route. In the case of using material with other thicknesses, not included in table 1, the interpolation or extrapolating methods can be used. In the case of using other material grades, the additional researchers have to be conducted or necessary use the available data about material with similar physical properties.



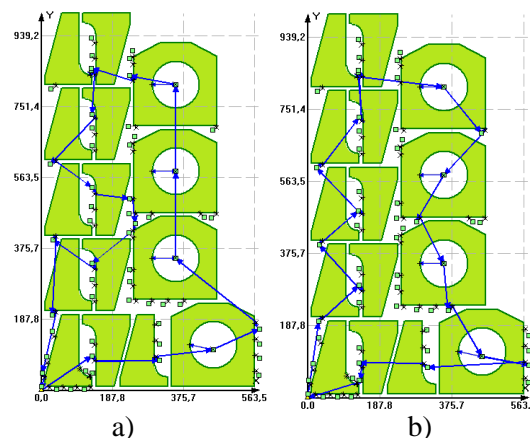
**Fig.3.** Change of the real cutting speed for AWAIMg3,  $\Delta=1$  mm

**Table 1.** The generalized table of formulas for calculating of cutting tool speed by example CNC laser cutting machine ByStar3015

Material and thickness of material $\Delta$	The predetermined cutting speed $V_{on}$ , m/s	The formulas for cutting tool speed calculation
1.0114, $\Delta=1$ mm	0,13	$V_{act} = -0.025 \cdot \ln(n) + 0.25$
1.0114, $\Delta=2$ mm	0,0975	$V_{act} = -0.015 \cdot \ln(n) + 0.1711$
1.0114, $\Delta=3$ mm	0,06	$V_{act} = -0.009 \cdot \ln(n) + 0.1062$
1.0114, $\Delta=3.5$ mm	0,042	$V_{act} = -0.006 \cdot \ln(n) + 0.0759$
1.0114, $\Delta=4$ mm	0,04	$V_{act} = -0.006 \cdot \ln(n) + 0.0709$
1.0114, $\Delta=8$ mm	0,027	$V_{act} = -0.003 \cdot \ln(n) + 0.0443$
1.0114, $\Delta=10$ mm	0,023	$V_{act} = -0.002 \cdot \ln(n) + 0.0359$
AWAIMg3, $\Delta=1$ mm	0,1	$V_{act} = -0.014 \cdot \ln(n) + 0.1589$
AWAIMg3, $\Delta=2$ mm	0,048	$V_{act} = -0.004 \cdot \ln(n) + 0.0641$
AWAIMg3, $\Delta=3$ mm	0,025	$V_{act} = -0.001 \cdot \ln(n) + 0.0315$
AWAIMg3, $\Delta=5$ mm	0,015	$V_{act} = -7 \cdot 10^{-4} \cdot \ln(n) + 0.0182$

### 3. Computing experiment

The example of cutting time optimization during cutting of 15 parts (material grade is AWAIMg3,  $\Delta=1\text{mm}$ ) was calculated using special module developed for russian CAM system „SIRIUS”. The nesting (Fig.4) consists of 15 parts (2 dimension type), the number of contours is 19. The each contour is cut with one cutting segment (i.e. the standard cutting technique is used). In order to reduce the acceptable solutions set of optimization problem the set of possible piercings was restricted with set consisting of 55 points (on the Fig.4 these points are indicated with green colour, corresponding switch tool off points are indicated with cross). The optimization of cutting time (objective function is  $T_{cut}$ ) was performed provided that  $V_{on} = \text{const}$  (Fig.4a) and  $V_{on} = \text{var}$  (Fig.4b), i.e. for the case AWAIMg3,  $\Delta=1\text{mm}$   $V_{on} = -0.014 \cdot \ln(n) + 0.1589$ . The optimization of cutting tool path is carried out using exact method of dynamic programming **Hiba! A hivatkozási forrás nem található..** Fig.6a presents cutting tool path (idling tool motions is indicated with blue color) for which the value objective function (1) (provided that  $V_{on} = \text{const}$ ) is minimum ( $T_{cut} = 126,27\text{s}$ ). Fig.6b presents cutting tool path for which the value objective function (1) is calculated with  $V_{act} = \text{var} = -0.014 \cdot \ln(n) + 0.1589$  (according to table 1 for this grade of material). The number of commands in NC program for this example contains 120 commands ( $n=120$ ). Consequently actual cutting time for this example is turned out to be larger than for case in Fig.4a.



**Fig.4.** The nesting and optimal cutting tool path by time for 15 parts (grade is AWAIMg3,  $\Delta=1\text{mm}$ ) provided that  $V_{on} = \text{const} = 0,1\text{m/s}$  (a) and  $V_{on} = \text{var} = -0.014 \cdot \ln(n) + 0.1589$  (b)

Using value  $V_{on} = -0.014 \cdot \ln(n) + 0.1589$  in objective function (1) the optimization gives another optimal solution of problem that is presented on Fig.4b. Wherein  $T_{cut} = 141,38\text{s}$ . Thus the exact calculation of objective function for the considered example provides not only the exact calculation of extremum objective function but also correct result of the optimal tool path search.

### 4. Conclusions

In this paper the following results were obtained:

1. The reasons of exact calculation of objective function during thermal cutting are formulated;
2. The change of thermal field in sheet material during cutting process does not affect on working speed;
3. The working speed depends on geometrical configuration of parts. As practice showed the more straight section in the nesting the working speed is increased. In the case of rectangle parts with and without rounding on the corner if there are rounding on the corner, the working speed will increase (and besides the more rounding the working speed increases);
4. The working speed depends on number of commands in NC program. The correction formulas of  $V_{on}$  calculation are presented in this article for the CNC laser ( $\text{CO}_2$ ) cutting machines.



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